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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 4 : G01H 9/00, G01D 5/26

A1

(11) International Publication Number: WO 86/ 05271

(43) International Publication Date: 12 September 1986 (12.09.86)

(21) International Application Number: PCT/GB86/00089

(22) International Filing Date: 21 February 1986 (21.02.86)

(31) Priority Application Number: 8504987

(32) Priority Date: 27 February 1985 (27.02.85)

(33) Priority Country: GB

(71) Applicant *(for all designated States except US)*: UNIVERSITY OF STRATHCLYDE [GB/GB]; McCance Building, 16 Richmond Street, Glasgow G1 1XQ (GB).

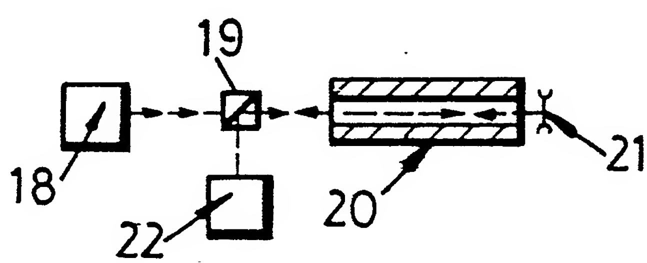
(72) Inventor; and
(75) Inventor/Applicant *(for US only)* : CULSHAW, Brian [GB/GB]; Cromdale, Gryffe Road, Kilmacolm, Renfrewshire PA13 4BD (GB).

(74) Agents: McCALLUM, William, Potter et al.; Cruikshank & Fairweather, 19 Royal Exchange Square, Glasgow G1 3AE (GB).

(81) Designated States: AT (European patent), AU, BE (European patent), BR, CH (European patent), DE (European patent), DK, FI, FR (European patent), GB (European patent), IT (European patent), JP, KR, LU (European patent), NL (European patent), NO, SE (European patent), US.

Published
With international search report.

(54) Title: A MEASURING DEVICE



(57) Abstract

The magnitudes of physical variables are sensed by measuring the resonant frequency of a vibratable structure (21). The structure (21) is of micromechanical form, conveniently etched from a wafer of semi conductor material, and is caused to vibrate by incident optical energy delivered via fibre optic wave guides (20) from a source (18) such as a laser.

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A MEASURING DEVICE

The present invention relates to a measuring device, and, in particular, to a measuring device in which the resonant frequency of a vibratable structure is a function of a measurand to be measured and the resonant frequency of the vibratable structure is detected to determine the value of the measurand.

It is known that the resonant frequency of a mechanical structure can be varied by changing the shape of the structure and/or by changing the ambient conditions prevailing around the structure. This is illustrated by the case of a string tensioned between two ends of a support structure, for which the resonant frequency is given by the formulae:

$$fo = \frac{1}{2l}\sqrt{\frac{T}{m}}$$

where T is the tension in the string, l is the length of the string and m is the mass per unit length.

The length of the string and the dimensions of the support structure are both temperature dependent and accordingly the variables T, l and m will alter with temperature giving rise to variations in the resonant frequency of the string. By determining the resonant frequency of the string it is possible to obtain a measure of the ambient temperature.

Moreover, by interfacing the support structure to a measurand so that variations in the measurand give rise to variations in the tension of the string a measure of the measurand can be obtained by determining the resonant frequency of the string.

The above described technique is well known and finds application in a vibrating wire gauge. The vibrating wire gauge comprises an electrically conductive wire which is tensioned between two ends of a support structure and on either side of which are positioned the opposing poles of a magnet. The tension in the wire is a function of the

measurand to be measured. This may be achieved by the measurand acting directly on the wire and support structure, as in the case of temperature, or by means of a suitable interface which acts through the support structure to alter the tension in the wire in response to the measurand, as in the case of, for example, mechanical strain. An electrical pulse is applied to the wire which has the effect of causing it to vibrate at its resonant frequency. As it is positioned between the opposing poles of a magnet an alternating voltage will be induced in the wire at this resonant frequency which can then be determined using conventional electronic techniques to provide a measure of the measurand.

Unfortunately, the vibrating wire gauge suffers from a number of inherent disadvantages. One of these is that the leads to and from the gauge are prone to electromagnetic interference which can distort the preceived alternating voltage induced in the wire as it vibrates between the opposing poles of the magnet. This problem is made worse when the vibrating wire gauge is used with long signal transmission lines. Another, is that by relying upon electrical signals, both to excite the wire into vibration and to provide a measure of the resonant frequency of vibration of the wire, the gauge is unsuitable for use in certain applications, such as, for example, measuring the temperature in an electrolytic solution.

It is an object of the present invention to provide a measuring device in which the problems associated with conventional vibrating wire gauges are obviated or substantially mitigated.

According to the present invention there is provided a device for measuring a measurand comprising a source of optical energy, a vibratable structure having a resonant frequency of vibration which is a function of the measurand and upon which optical energy from said source

is incident, said incident optical energy causing the structure to vibrate at said resonant frequency and to modulate optical energy reflected from the structure at said resonant frequency, detection means for detecting optical energy reflected from the structure and determining the frequency of modulation thereof and display means for displaying the value of the measurand corresponding to the frequency of modulation.

Preferably the vibratable structure is fabricated from a crystalline material, for example silicon or gallium arsenide.

The surface of the vibratable structure upon which the optical energy is incident may be coated with a layer of partially reflective partially absorptive material, for example, gold. As yet it is not fully understood by what mechanism the incident optical energy causes the vibratable structure to vibrate, but it is thought possible that the absorption of energy by the vibratable structure causes heating thereof which sets it vibrating.

The vibratable structure may comprise a beam secured at each end to a support structure or alternatively a diaphragm secured around its periphery to a support structure. The support structure may be directly affected by the measurand, as for example in the case of temperature, or may be affected by the measurand through some form of interface. Where an interface is used it may comprise a selectively absorptive layer of material which coats the vibratable structure. The layer of material selectively assimulates material in the environment of the vibratable structure and according to its concentration alters the mass thereof and thence the frequency of vibration. It may also cause localised heating which also alters the frequency of vibration.

Preferably, optical energy is transmitted from the source of optical energy to the vibratable structure, and

from the vibratable structure to the detector means, via optical transmission lines comprising at least one fibre optic wave guide.

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Fig. 1 shows a schematic block diagram of a measuring device embodying the present invention;

Fig. 2 shows an end view of a vibratable bridge microstructure for use in a measuring device embodying the present invention;

Figs. 3(a), (b) and (c) each show a schematic diagram of an embodiment of the present invention, each employing different optical transmission techniques;

Fig. 4 shows a schematic diagram of a measuring device embodying the present invention employing two sources of optical energy and a fibre optic transmission network; and

Fig. 5 shows a detailed view of the optical components in an embodiment of the present invention of Fig. 4.

Referring to the schematic block diagram of Fig. 1 there is shown a source of optical energy 1, that is ultra-violet, visible or infra-red radiation which may comprise a directly modulated semiconductor laser, a light emitting diode (LED) or a gas tube laser with an external modulating system. Optical energy from the source 1 is directed via an optical transmission line 2 onto a micro-mechanical structure 3 having vibratable structure (not shown) which has frequency of vibration which is a function of a measurand to be measured and is excited into vibration when optical energy is incident thereon. The surface of the vibratable structure upon which the optical energy is incident is reflective and as a consequence optical energy reflected from it is modulated at the frequency at which it vibrates, that is at its resonant

frequency of vibration. The modulated optical energy reflected from the vibratable structure is directed via a second optical transmission line 4 to a detector device 5 which is capable of determining the frequency of modulation. Since the frequency of modulation corresponds to the resonant frequency of vibration of the vibratable structure which is itself a function of the measurand, the frequency of modulation provides a measure of the value of the measurand. Using appropriate calibration techniques and display devices this can then be displayed as the actual value of the measurand.

The source of optical energy 1 is modulated over a wide range of frequencies up to and exceeding the anticipated range of mechanical resonances of the vibratable structure upon which the optical energy is directed via optical transmission line 2.

The force exerted by the source of optical energy 1 upon the vibratable structure may be due simply to radiation pressure and is then given by the formula:

$$F = \frac{Pk}{c}$$

where c is the velocity of light, P is power of the optical energy and k is a component depending on the reflective co-efficient of the surface upon which the optical radiation impinges, having for highly reflective surfaces a value of the order of 2. Given that the reflectivity of the incident surface is at a maximum and that the optical radiation has a value of the order of 1mW, the force exerted is of the order of 10^{-11} Newtons. For a typical micromechanical structure having a vibratable structure of the type shown in Fig. 2 this is sufficient to cause a displacement of the order of a few nanometers which is easily detected. The forces exerted by the optical energy source 1 due to partial absorption followed by thermal expansion of the vibratable structure could actually be considerably larger, causing even more

easily detected displacements. In this respect, power levels in the range 0.1 to 1mW have been found to produce detectable displacements of the vibratable structure.

The optical transmission lines 2 and 4 both present a low attenuation to the optical energy transmitted therethrough and in this respect whilst a system of lenses transmitting light through air will work over short distances the transmission lines are ideally comprised of monomode fibre optic wave guides which can retain the light in a spot a few microns in diameter. Whilst the optical transmission lines 2 and 4 have been shown in Fig. 1 as two separate lines it will be understood that they may in fact be coincident with a suitable optical coupler provided at a convenient point thereon to couple the transmission line to the detector 5. This is described in greater detail with reference to Figs. 3(a), (b) and (c).

The detector device 5 is required to detect the frequency of modulation of the optical energy reflected from the micromechanical structure 3 and a number of techniques may be used for this purpose. By way of example the detector device 5 may rely on interferometric techniques to indicate the frequency of modulation, or alternatively may rely on monitoring the intensity or polarisation of the reflected optical energy which will both vary at the frequency of modulation.

As indicated hereinabove the resonant frequency of vibration of the vibratable structure of the micromechanical structure 3 is a function of the measurand to be measured which is applied to the vibratable micromechanical structure 3 either directly or indirectly using an interfacing device (not shown). The vibratable structure must be very small in order to be vibrated by the incident optical energy and dimensions of the order of one micron thick and ten to one hundred microns in

length and a few microns in width have been found to be ideal. Such small structures may be readily fabricated from certain semi-conductor materials, for instance silicon and gallium arsenide, using anisotropic etching techniques. Indeed, certain crystalline materials will themselves interact directly with the measurand of interest, for instance a garnet will interact with a magnetic field.

Referring to Fig. 2 there is shown an example of a micromechanical structure comprisng a silicon substrate 6 which has been etched away under a layer of silicon dioxide 7 deposited thereon to form a silica bridge 8 to optimise the reflectivity and absorptivity of the micro-mechanical structure. After fabrication of the micro-mechanical structure has been completed the dimensions of the silica bridge 8 are typically several tens of microns in length, one micron in thickness and a few microns in width. Changes in the dimensions of the silicon substrate 8 caused by the measurand change the tension in the silica bridge 8 and as a consequence the resonant frequency at which the silica bridge 8 vibrates also changes.

Referring to Fig. 3(a) there is shown a schematic diagram of a measuring device embodying the present invention which comprises a source of optical energy 10 the output of which is applied to an optical beam splitter 11 which splits the beam in two and directs each of the resultant beams along respective optical transmission lines 12 and 13.

The optical energy in line 12 is directed through an optical device 14, which may allow light to pass through it in one direction, but not in the other or may be a beam splitter, onto the vibratable structure 15 of a micromechanical structure (not shown). The optical energy incident on the vibratable structure 15 causes it to

vibrate at its resonant frequency which is a function of the value of a measurand applied thereto. The surface of the vibratable structure 15 upon which the optical energy in line 12 is incident is reflected back onto the optical device 14 where it is directed towards a light detector 16. The optical energy in line 13 is also directed towards the detector 16, however it first passes through a frequency shifter 17. The path 13 through to the detector 16 forms the reference arm of a heterodyne interferometer in which the other arm goes through path 12 to the vibrating structure 15 via the optical device 14 to the detector 16. The optical energy reflected from the vibrating structure 15 is compared with the frequency shifted optical energy in line 13 at the light detector 16. The phase of the reflected optical energy will be modulated at the frequencies at which the vibrating structure 15 is vibrating. This phase modulation after photodetection is transferred to the diference frequency between the two beams in the interferometer and can then be detected using conventional electronic techniques.

Referring to Fig. 3(b) there is shown a schematic diagram of another embodiment of the present invention which comprises a source of optical energy 18 the output of which is directed via a beam splitter 19 and a fibre-optic wave guide 20 onto the vibratable structure 21 of a micromechanical structure (not shown). Optical energy reflected from the vibratable structure 21 is modulated at the resonant frequency of vibration of the vibratable structure 21 which is a function of a measurand. The surface of the vibratable structure 21 upon which the optical energy is incident and the end of the fibre-optic wave guide 20 facing the vibratable structure 21 together define a Fabry-Perot cavity. As the vibratable structure 21 vibrates towards and away from the end of the fibre-optic wave guide 20 the size of the Fabry-Perot cavity

changes in sympathy with the vibrations of the vibratable structure 21. This has the effect of modulating both the frequency and intensity of the optical energy reflected back down the fibre-optic wave guide 20.

The reflected optical energy passes down the fibre-optic wave guide 20 to the beam splitter 19 where it is directed to a detector 22 which is able to determine the frequency of intensity and/or frequency modulation thereof.

A further embodiment of the present invention is shown in Fig. 3(c) in which a wide beam of optical energy from a source of optical energy 23 is directed onto the vibratable structure 24 of a micromechanical structure (not shown) via a beam splitter 25, a fibre-optic wave guide 26 and a focusing lens 27. Optical energy reflected from the structure 24 is collected by the lens 26 and directed back along the fibre-optic wave guide 25 to the beam splitter 24, which in turn directs the optical energy to a detection device 28. The detector device 28 is capable of detecting changes in the intensity of the reflected optical energy arising from the vibrations of the vibratable structure 24.

Fig. 4 shows a schematic diagram of a further embodiment of the present invention comprising an amplitude modulated source of optical energy 29 which is applied to the vibratable structure 30 of a micromechanical structure (not shown). Optical energy from a second source 31 is also applied to the vibratable structure 30 and the reflected beam of optical energy is modulated at the frequency of vibration of the vibratable structure 30. The reflected optical energy is compared with a reference beam of optical energy which is derived from the second source of optical energy 31 after first passing through a frequency shifter 32, to form a modified heterodyning Mach-Zehnder interferometer in which the phondetector 33

detects the frequency of modulation.

Fig. 5 shows the embodiment of the present invention of Fig. 4 comprised of discrete components.

As the measuring device of the present invention relies on optical energy of very low levels to excite the micromechanical structure and be a carrier for the resonant frequency of vibration thereof, the micromechanical structure is intrinsically safe in use.

In addition, as the micromechanical structure is very small it may be readily bonded to the end of an optical fibre to provide an extremely small and very compact sensor. In fact, with optical fibres typically having a diameter of the order of 100 microns it is possible to mount both optical fibre and micromechanical structure in the bore of a hyperdermic needle. Such an arrangement means that the sensor can be easily introduced into awkward environments, for example, the human body without materially affecting the environment.

As the micromechanical structure can be readily fabricated from any one of a variety of crystalline materials it will usually be possible to choose a material which is inert in the environment in which it is intended to use it thus avoiding corrosion problems. Moreover, as the micromechanical structure is fabricated from crystalline materials high precision batch production techniques, based on standard semiconductor fabrication techniques, may be used to produce large numbers of the micromechanical structures at low costs.

Whilst the present invention has been described with reference to one micromechanical structure using a single transmission line, it will be appreciated that a number of micromechanical structures may be interfaced to one transmission line and that they may be multiplexed to share the transmission line. The micromechanical structures may be in different locations to sense the

same measurand in different areas of a system or may all be located together and each sense a different measurand.

The vibratable structure described hereinbefore comprised a bridge or beam supported at each end, however other arrangements are also envisaged. For example, the vibratable structure may comprise a diaphragm which is support around its periphery. By making the space under the diaphragm airtight it is possible to provide a pressure sensitive sensor.

CLAIMS

1. A device for measuring a measurand characterised by a source (10) of optical energy, a vibratable structure (15) having a resonant frequency of vibration which is a function of the measurand and upon which optical energy from said source (10) is incident, said incident optical energy causing the structure (15) to vibrate at said resonant frequency and to modulate optical energy reflected from the structure (15) at said resonant frequency, detection means (16) for detecting optical energy reflected from the structure (15) and determining the frequency of modulation thereof and display means (16) for displaying the value of the measurand corresponding to the frequency of modulation.

2. A device as claimed in claim 1, characterised in that the surface of the vibratable structure upon which the optical energy is incident is coated with a layer of reflective material.

3. A device as claimed in either preceding claim, characterised in that the vibratable structure is fabricated from a crystalline material.

4. A device as claimed in any preceding claim, characterised in that the vibratable structure is in the form of a beam (8) mounted at its ends on a support structure (6).

5. A device as claimed in any one of claims 1-3, characterised in that the vibratable structure is in the form of a diaphragm secured around its periphery to a support structure.

6. A device as claimed in any preceding claim, characterised in that the optical energy is transmitted from the source of optical energy (10) to the vibratable structure (15) and from said structure (15) to the detection means

(16) via optical transmission lines comprising at least one fibre optic wave guide (20).

7. A device as claimed in any preceding claim, characterised in that said optical source (10) is a laser source (31).

8. A device as claimed in any one of claims 1-6, characterised in that said optical source (10) is a light emitting diode (29).

9. A device as claimed in claim 1, characterised in that said vibratable structure is formed in semi conductor material (6) by etching.

10. A device as claimed in claim 1, and substantially as hereinbefore described by way of example with reference to any one of the embodiments illustrated in the accompanying drawing.

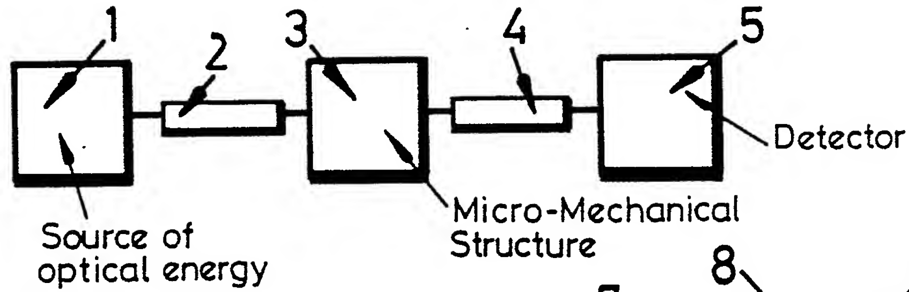

FIG.1

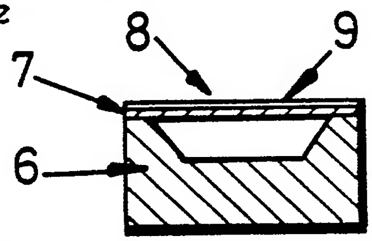

FIG.2

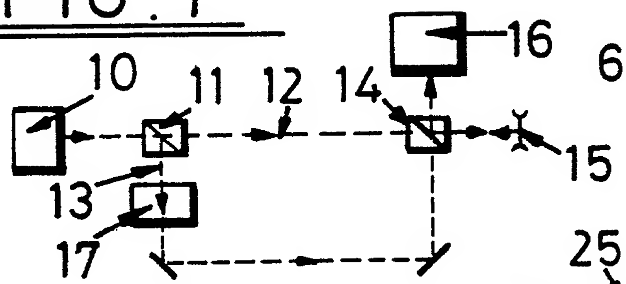

FIG.3a

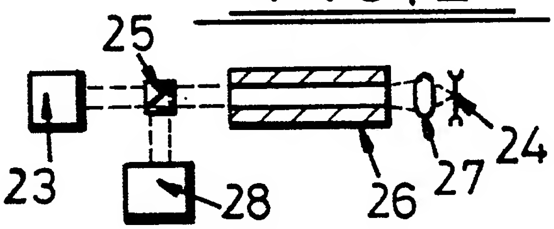

FIG.3c

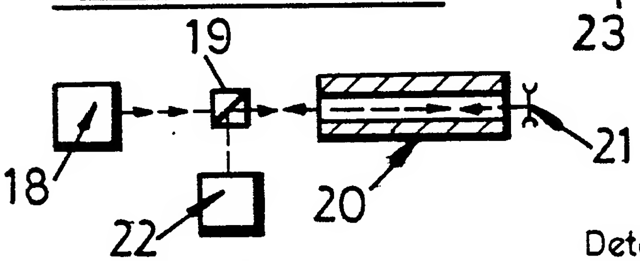

FIG.3b

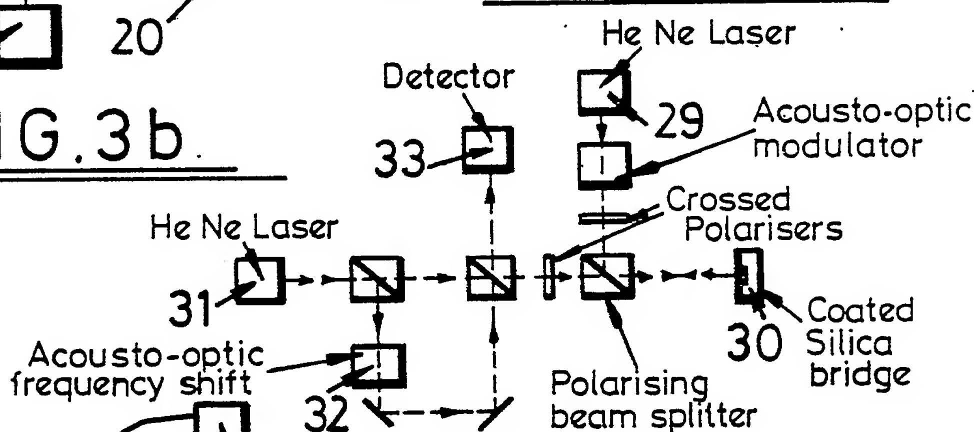

FIG.5

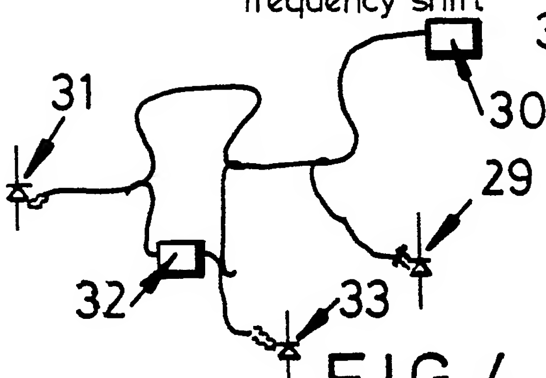

FIG.4

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 86/00089

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^4: G 01 H 9/00; G 01 D 5/26

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^4	G 01 H G 01 L G 01 D

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category [*]	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	EP, A, 0090167 (THE FOXBORO CY.) 5 October 1983, see abstract; page 4, lines 30-33; claim 1	1,2,4,6,8, 10
	--	
X	Patents Abstracts of Japan, volume 6, no. 96 (P120)(974), 4 June 1982, & JP, A, 55105939 (SHIMAZU SEISAKUSHO) 19 February 1982, see full text	1,5,6,7
	--	
A	Regelungstechnische Praxis, volume 25, no. 12, December 1983, München, (DE) A. Schwaier:"Optische Aufnehmer und Verfahren für die Prozesstechnik", pages 503-509, see page 505, column 1, line 33 - column 2, line 9; figures 1,2	1,3,9
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[*] Special categories of cited documents: [10]

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
16th April 1986	02 JUN 1986
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	M.A.J.G. VANMOL ☎ (070) 402008

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO. PCT/GB 86/00089 (SA 12238)

This Annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 06/05/86

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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
EP-A- 0090167	05/10/83	AU-A-	1160483	01/09/83
		JP-A-	58155320	16/09/83
		US-A-	4521684	04/06/85
		CA-A-	1196706	12/11/85

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